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The collaboration between Yale and the Westinghouse Science and Technology Center produced high quality, sub-micron, superconducting Nb trilayer tunnel junctions. These junctions were made using a fabrication process developed at Westinghouse as a result of this collaboration. The junctions were fabricated on thin (2 mil) quartz substrates using the existing facilities at Westinghouse. The quality of these devices compares favorably with others reported, particularly in the sub-micron size range. These junction were used as receiving elements in a broad-band 80-120 GHz mixer receiver. This receiver had no mechanical tuning elements. The noise of this receiver using these devices is among the lowest reported in the 80-120 GHz frequency band, particularly among those with no mechanical tuning elements.

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Final Technical Report of Progress on AFOSR-88-0270

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Results from the collaboration between Yale and the Westinghouse Science and Technology Center are presented here. Over the time period of this report, sub-micron Nb trilayer tunnel junctions were fabricated and tested. These junctions were made using a novel fabrication technique, specially suited for fabrication of sub-micron tunnel junctions using the existing facilities at Westinghouse. A discussion of the fabrication procedures, junction quality, and results of high frequency heterodyne experiments are presented below.

The junctions were fabricated at the Westinghouse by graduate student Anthony Worsham. In the approximately 17 weeks that he was working with the cryogenic group at Westinghouse, he developed a modified Selective Niobium Insulator Process (SNIP) which produced high quality sub-micron tunnel junctions. All of the devices were fabricated on 1 inch x 1 inch x 2 mil thick quartz substrates. Worsham developed a fabrication process in which these quartz substrates were mounted to 2 inch diameter Si wafers using vacuum grease. The processing of the quartz was then able to use the equipment at Westinghouse which had been standardized to 2 inch diameter wafers.

It is difficult to fabricate small (5 μm^2 or less) trilayer tunnel junctions using standard device insulation processes since these require a separate mask for patterning of the insulator. This would require a very difficult alignment to the small tunnel junction to define a contact hole. Existing processes at Westinghouse using a Self Aligned Niobium Anodization Process (SNAP) produced high quality tunnel junctions whose sizes were as small as 5 $(\mu m)^2$. The high quality of these junctions (V_m as large as 60 mV) showed that the trilayer quality was excellent. Unfortunately, it was not possible to extend the existing

Westinghouse process to junction sizes smaller than 2 $(\mu m)^2$ since the anodization causes stress in the Nb film, leading to degraded I-V curves.

After attempts to use anodization to define a junction with area of 1 $(\mu m)^2$ failed, a modified SNIP process was developed. This process was ideal for the production of the small tunnel junctions since it used etching to define the tunnel junction and thus caused no stress to the Nb films. A schematic side view of the fabrication procedure is shown in Fig. 1. First, 100 Å of Al was sputter deposited to the quartz substrate. This Al underlayer was necessary since the trilayer on top of it was patterned by lift-off. Without this thin Al layer, it was not possible to resolve the 2 µm mask features in the lift-off resist stencil since back-side reflection from the transparent quartz caused blurring of the exposed pattern. The Al underlayer also served to protect the quartz substrate from etching. For the application of lift-off lithography, an image-reversal photoresist process was developed. This process gave an undercut profile to the resist, thus allowing subsequent metal depositions to be discontinuous across the resist edge and thus assuring good in lift-off (Fig. 1a). After defining the photoresist, the trilayer (2500 Å Nb, 100 Å Al oxidized, 800 Å Nb) was sputtered deposited and lifted-off. The wafer was heat-sunk well to the copper mounting block in the sputtering system. This allowed for the patterning of sputter deposited films by liftoff, since without adequate heat sinking, the resist would harden during the metal depositions.

The junctions were 0.5, 2, and 4 $(\mu m)^2$ in area. Series array of up to 12 junctions were fabricated with current densities of 3000 and 5000 A/cm^2. The junction area was defined by a reactive ion etch of the Nb counter-electrode. This etch was stopped at the AlO_x. (Fig. 1b). The resist profile was then "shrunk" in an O_2 plasma. This shrinkage ensured adequate step coverage by the subsequent deposition of an insulator. Subsequent to the O_2 plasma etch, but without removing the resist stencil, a wet etch removed the remaining exposed Al underlayer, as well as the exposed Al in the trilayer. The remaining underlayer was only under unpatterned trilayer, thus was always electrically shunted by the trilayer. A sputter deposition of SiO_2 and subsequent lift-off ensured that the junction was defined and isolated (Fig. 1c). The device was completed by defining a Nb wiring layer by lift-off, and depositing a Nb ground plane on the back side of the quartz substrate (Fig. 1d).

The junctions fabricated at Westinghouse using the modified SNIP process compare favorably with others reported, particularly among sub-micron devices. In addition, the use of the thin quartz as a substrate material represented a real accomplishment. The thin quartz substrates were necessary for the microwave receiver applications, since thicker substrates could give radiative losses. The best measured devices had V_m(2 mV) = 50 mV at 4.4 K. Most devices had $V_m > 20$ mV.

The devices fabricated at Westinghouse were used as the receiving elements in a broad-band 80-120 GHz heterodyne receiver with no mechanical tuning. For this design, it was important that the SIS devices be small, since a large capacitance of the junction would limit the observation bandwidth by shunting the high frequency signal. The measured receiver noise temperature of a number of devices is shown in Fig. 2. These low noise results compare favorably with other groups reporting in this frequency range, particularly among receivers with no mechanical tuning elements.

A number of physics issues have subsequently been studied using the receiver at Yale and the devices fabricated at Westinghouse. Since the fabricated tunnel junctions are small area and small capacitance, it is possible to study the fundamental tunneling currents in a superconducting tunnel junction. This was done by employing a waveguide impedance measurement. Since the device capacitance is small, the fundamental reactive quasiparticle currents have an admittance which is of the same order of magnitude as the admittance of the capacitance. Thus, by performing an impedance measurement, one can observe the effects of the reactive quasiparticle currents. Once measured and understood, the reactive tunneling current can be used for applications such as a electrically tunable inductance. This would be useful in forthcoming designs of THz receivers, where it is difficult to fabricate and characterize variable impedance elements. The tunnel junctions and waveguide impedance measurement can also be used to differentiate between the current due to sequential, coherent tunneling and that due to inelastic tunneling. This is of interest because of the lack of understanding of the effect of the unoxidized Al in the tunnel barrier on the tunneling properties. This Al causes the proximity effect, common to all Nb trilayer devices with unoxidized Al. This Al may also influence the nature of the trap states in the barrier and can be studied using the devices fabricated at Westinghouse.

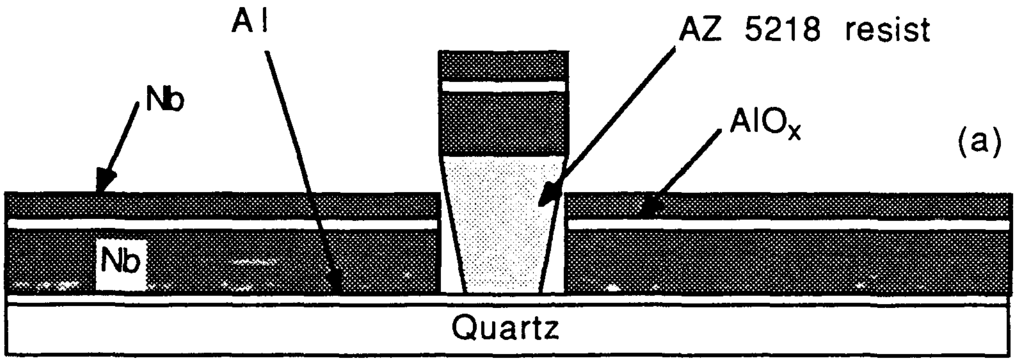
In summary, the collaboration between Yale and the Westinghouse Science and Technology Center yielded high quality sub-micron Nb trilayer tunnel junction. These junctions were used as receiving elements in a broad-band mixer receiver. The results for the receiver and the junctions themselves compare favorably with others reported in the frequency and size range respectively. In addition, the collaboration yielded a fabrication process which could be used by Westinghouse to fabricate small, trilayer tunnel junctions using their existing facilities. This may be important since further developments at higher frequencies will require smaller tunnel junction areas, and smaller associated capacitances.

Publications resulting from the Yale-Westinghouse Collaboration

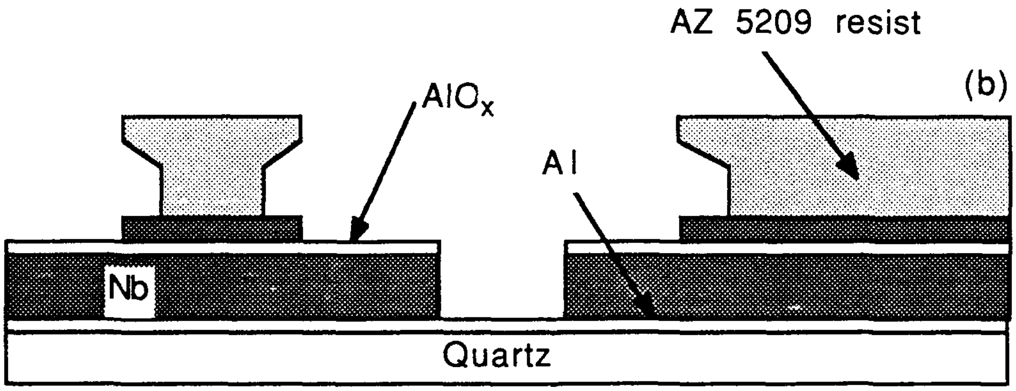
A.H. Worsham, D.E. Prober, J.H. Kang, J.X. Przybysz, and M.J. Rooks, "High quality sub-micron Nb trilayer tunnel junctions for a 100 GHz SIS receiver," IEEE Trans. Magn., MAG-27, 3165 (1991).

D. Winkler, N.G. Ugras, A.H. Worsham, D.E. Prober, N.R. Erickson, and P.F. Goldsmith, "A full-band waveguide SIS receiver with integrated tuning for 75-110 GHz," IEEE Trans. Magn., MAG-27, 2634 (1991).

D. Winkler, A.H. Worsham, N.G. Ugras, D.E. Prober, N.R. Erickson, and P.F. Goldsmith, " A 75-110 GHz SIS mixer with integrated tuning and coupled gain," in: Nonlinear Superconductive Electronics and Josephson Devices, N.F. Pedersen, M. Russo, A. Davidson, G. Constabile, and S. Pagano, eds., Plenum, London, 1991.

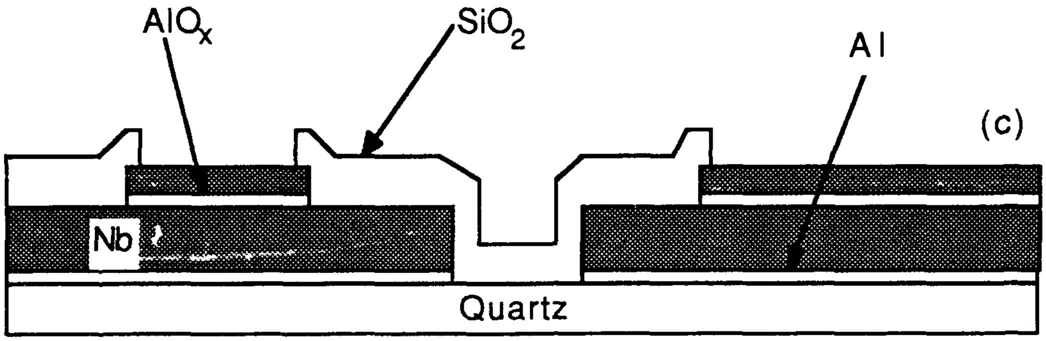


Trilayer deposition and lift-off

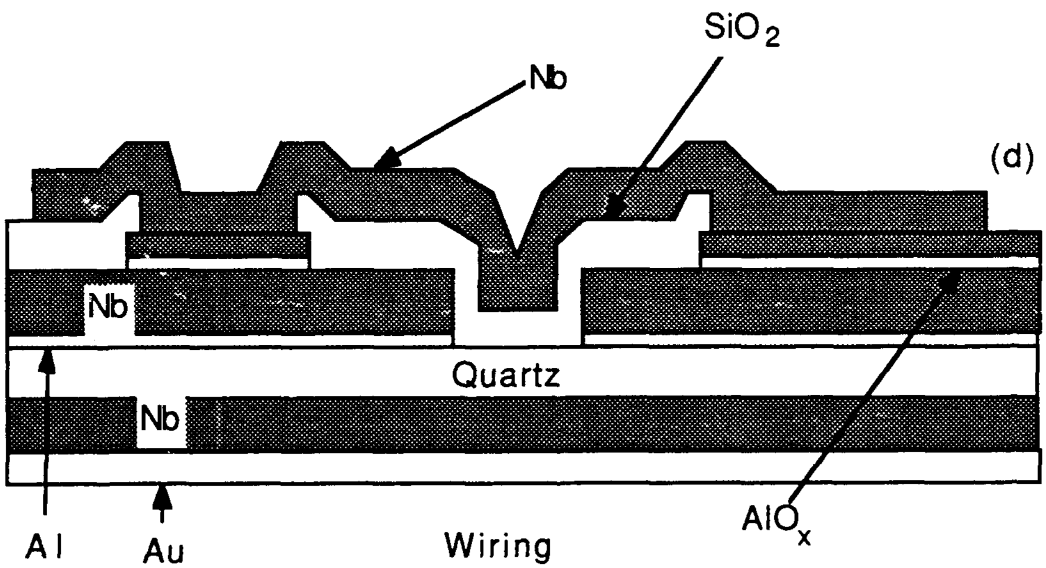


Junction definition and RIE

Fig. 1



Insulator deposition and lift-off



Wiring

Fig. 1 cont.

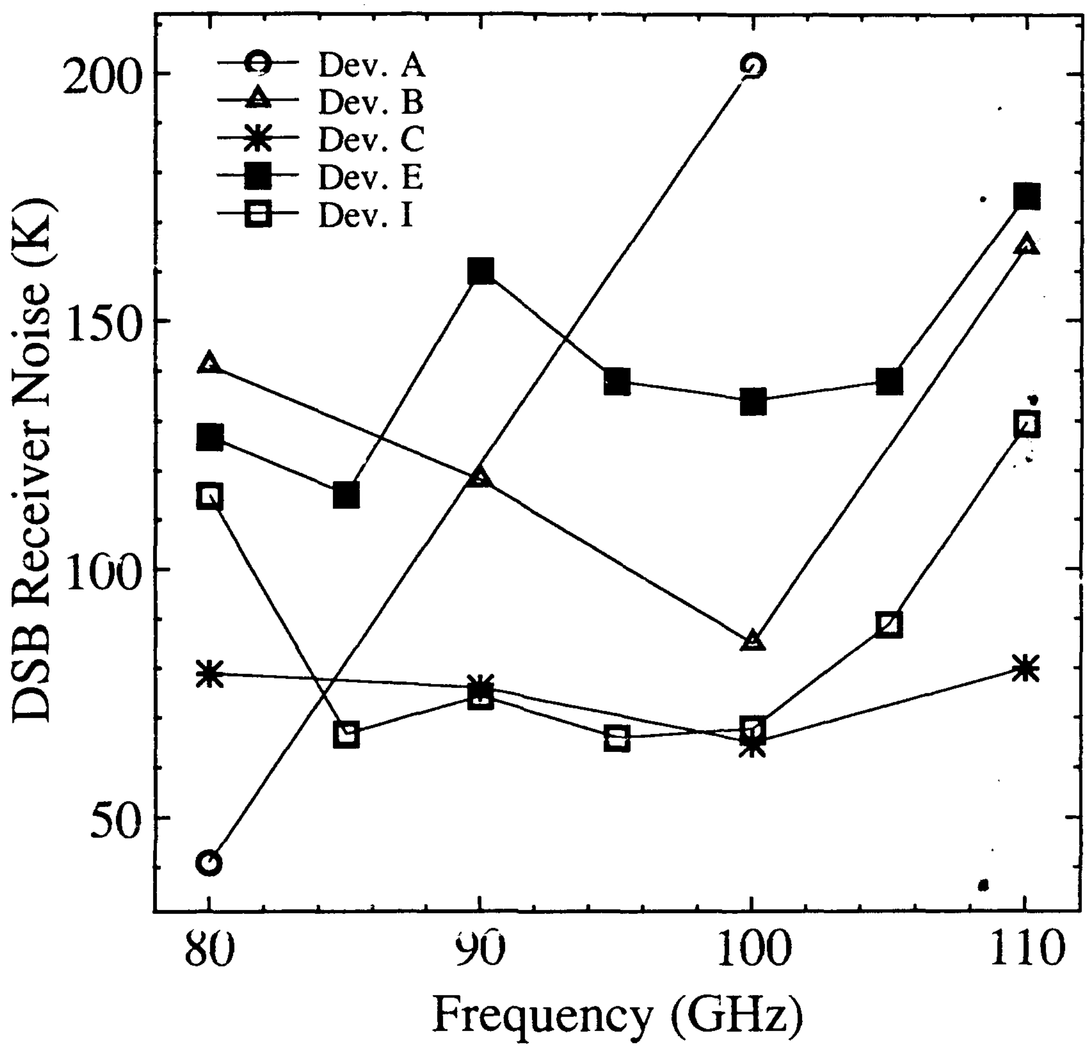


Fig. 2 DSB Receiver noise temperature for selected devices.